Off-road mobile robot control: An adaptive approach for accuracy and integrity

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Abstract This paper proposes an algorithm dedicated to the control of off-road mobile robots at high speed. Based on adaptive and predictive principles, it first proposes a control law to preserve a high level of accuracy in the path tracking problem. Next, the dynamic model used for grip condition estimation is considered to address also robot integrity preservation thanks to the velocity limitation.

1 Introduction

Mobile robotics, especially in off-road context, appears as a promising answer to future needs in various fields of applications [Siegwart and Nourbakhsh (2004)], such as farming [Eaton et al. (2009)], surveillance [Schafer et al. (2008)], or military activities. In order to be efficient, such automatic devices must be accurate, efficient and robust, despite the harsh conditions encountered. If many approaches dedicated to on-road vehicles have been proposed (kinematic [Micaelli and Samson (1993)] or dynamic [Andréa-Novel et al. (1995)] model based), they are not suitable to address off-road path tracking at high speed. Indeed, they either do not describe encountered dynamic phenomena or they require the knowledge of many parameters, which can not be considered as constant in the considered context. Moreover, the fast off-road motion implies some risks for the robot integrity (rollover or spin around), which have to be accounted in the motion control.

In this paper, an adaptive and predictive approach, taking advantage of several levels of modeling is proposed. It permits to preserve the model tractability thanks to a reduced number of parameters (representative of grip conditions) on-line estimated. Based on this representation, a control law is derived for the steering angle, ensuring a good tracking accuracy whatever the grip conditions and the path to be followed, independently from the robot velocity. As a result, the robot speed can be designed in order to preserve the robot integrity, without changing the tracking performances. Then, the paper is organized as follows. First, the different levels of modeling are described and their relationships are highlighted. As this overall model requires the knowledge of some unmeasurable variables and parameters, an observer based on this multi-model point of view is developed. Once the model is entirely known, the control strategy for path tracking and integrity preservation is presented. The efficiency of the proposed approach is investigated through full-scale experiments.

2 Robot models

In order to permit an accurate off-road path tracking at high speed, the proposed control algorithm takes advantage of several levels of representation, as depicted in figure 1. The first level is based on a kinematical representation and is so called **extended kinematic model**. It allows to describe robot motion including the influence of sliding. Based on Ackermann model [Campion et al. (1993)] and detailed in [Lenain et al. (2006)], it is designed with respect to a reference trajectory, describing the evolution of the curvilinear abscissa, the lateral and angular deviations, with respect to the two control variables: the velocity at the middle of the rear axle and the front steering angle. This model accounts for sliding effects by the introduction of two sideslip angles on the two axles of the bicycle representation. The main advantage of this point of view lies in the fact that kinematic description of motion is preserved, allowing to derive a control law thanks to exact linearization techniques, as discussed in control section. Moreover, the estimation of sideslip angles at low speed can be proceeded thanks to this model (see the observer section). This level of representation is then sufficient for the motion control at limited speed. Nevertheless, dynamical effects are here neglected, and such a model appears to be inefficient when moving faster. As a consequence, a dynamic model is then required for fast sideslip angle estimation as well as for the preservation of the mobile robot integrity.

A 3D dynamical model is then considered using two 2D representations:

- **Dynamic model 1 (yaw frame)**. It is still based on the bicycle

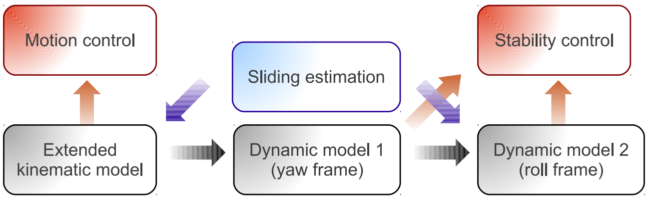


Figure 1. Synopsis of considered modeling and interaction

assumption, as achieved in [Gillespie (1992)] or in [Ben Amar and Bidaud (1995)]. In addition to variables used for the kinematic representation, the global sideslip angle and the robot inclination are introduced. Since the path tracking task is here supposed to be performed with a slow varying velocity, the longitudinal forces are neglected. As a result, only the lateral components of contact forces (for the front and rear axles) are here considered. In order to be tractable, complex tire-soil interaction models (such as proposed in [Pacejka (2002)]) are avoided: these forces are considered to be linearly dependent on front and rear sideslip angles. The linear coefficients (namely cornering stiffnesses) are nevertheless considered as varying (estimated by an observer), allowing to account for contact variability and tire non-linearity.

- **Dynamic model 2 (roll frame)**. It is fed by the outputs of dynamic variables computed thanks to the yaw frame representation. It depicts the roll motion and is devoted to the computation of the robot lateral rollover risk. Only the normal forces F_{n1} and F_{n2} (for the left and right sides) are then considered at the tire/ground contact interfaces. In order to evaluate the stability, this model is focused on the Lateral Load Transfer (LLT) computation, which is defined by $LLT = \frac{F_{n1}-F_{n2}}{F_{n1}+F_{n2}}$ and is representative of the mass repartition on robot sides. If this metric reaches ± 1, it means that two wheels of one side of the robot lift off.

The detailed equations of this model can be found in [Bouton et al. (2010)], and need several kinds of parameters. First, the "invariant" parameters, which can be obtained by an off-line calibration procedure (such as the robot mass). Secondly, grip conditions parameters (contact variability and tire non-linearity), which are hardly measurable, and consequently estimated.

3 Multi-model observer

As mentioned in the previous section, the proposed models can be used to proceed motion and stability controls as soon as sideslip angles and cornering stiffnesses are correctly known (i.e. with a sufficient reactivity and accuracy). The other variables and parameters can indeed be measured by the sensors on-boarded, described in section 5.1, or off-line evaluated thanks to a previous calibration.

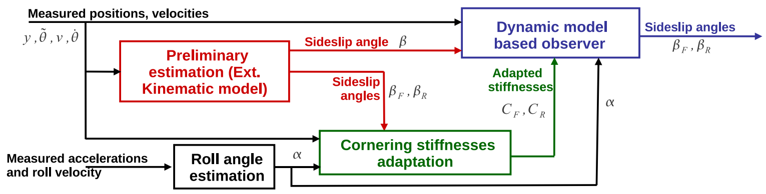


Figure 2. Global scheme of observation strategy

The proposed observer takes advantage of the relationship between kinematic and dynamic representations thanks to the backstepping approach depicted in figure 2. First, a **preliminary observation** based on the extended kinematic model is achieved. An estimation of sideslip angles is indeed obtained thanks to the convergence of kinematic model outputs to the measured lateral and angular deviations, as detailed in [Lenain et al. (2006)]. Alas, dynamical effects are neglected, leading to a slow-varying sideslip angle estimation, unsuitable when moving at high speed. Dynamic model 1 must be used to allow a faster adaptation. Nevertheless, such a model must be fed with the inclination of the suspended mass (measured by an accelerometer) and relevant values of cornering stiffnesses. They are on-line adapted thanks to a second step (**Cornering stiffnesses adaptation**). As slow-varying estimations of sideslip angles are available, they are used to calculate the robot global sideslip angle, considered as a measure in the sequel. A relevant value for cornering stiffnesses can then be evaluated, by ensuring the convergence of the dynamic model outputs to the measured yaw rate and global sideslip angle. The dynamic model is then totally known, and can finally be used to build an observer for the fast estimation of the sideslip angles. This last step is depicted by the box **Dynamic model-based observer** in figure 2. The detailed equations of this observer (but neglecting for the robot inclination) can be found in [Lenain et al. (2011)]. Finally, the overall dynamic model is entirely known, enabling the fast observation of sideslip angles and the control of the robot integrity.

4 Motion control and integrity preservation

4.1 Accurate trajectory control algorithm

The control law associated with the extended kinematic model is deeply detailed in [Lenain et al. (2006)], and only briefly described in this section. It is based on an exact linearization of the proposed kinematic model, specifically a conversion into a chained form (see [Samson (1995)]). The control expression for the steering angle is then decomposed into two parts. The first term is reactive and relies mainly on current errors and observed sideslip angles. It can be then considered as adaptive, since it relies on the observed sideslip angles. The second term consists in a predictive curvature servoing using the knowledge of the reference trajectory. Based on Model Predictive Control theory (see [Richalet (1993)]), it considers the future path curvature in order to anticipate for low level actuator delays and mobile robot inertia.

4.2 Preservation of the mobile robot integrity

If the proposed control strategy fed with the observed sideslip angles allows to control accurately the robot motion at high speed and on different kinds of ground, it does not ensure the robot integrity. More precisely, the steering angle thus obtained, pending on the desired speed and on the terrain geometry, may generate hazardous situations, such as rollover or spin around, which are not considered within the above described path tracking control law.

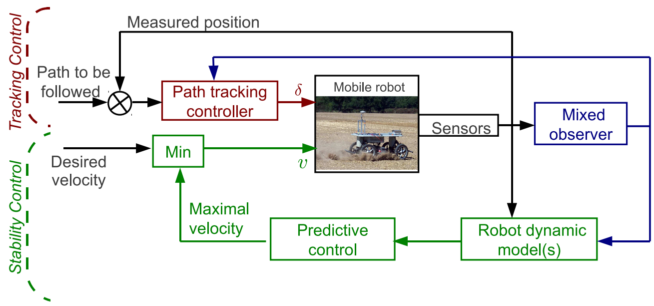


Figure 3. Global control scheme of autonomous robot

In order to design a robust control algorithm with respect to such phenomena, the second control variable (the robot velocity) is no more considered as a constant to be chosen at the beginning of the path tracking, but as a degree of freedom, allowing to maintain the robot in a safe behavior. Since a dynamic representation is available, the relationship between the velocity and the variables describing robot integrity can be derived. In this framework, the influence of speed on the lateral load transfer and steering angle, pending on observed grip conditions is considered. Using a predictive algorithm, the velocity leading to a chosen threshold for LLT or maximal steering angle is computed. It is then considered as the maximal velocity to be applied to the robot to preserve its integrity. The global control strategy can then be summarized by the scheme proposed in figure 3. Detailed equations for velocity limitation can be found in [Bouton et al. (2010)] for rollover prevention and in [Hach et al. (2011)] regarding the steering saturation.

5 Experimental results

5.1 Experimental robot and on-boarded sensors

In order to study the capabilities of the proposed adaptive control strategy on uneven ground, the mobile robot depicted in figure 4 is used. This electric vehicle can reach a 8m/s velocity and is able to climb slopes up to 30°. Its weight is 450Kg. The sensors used in the framework of this paper are:

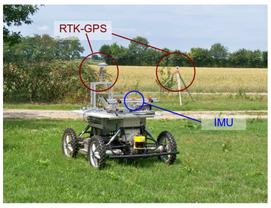


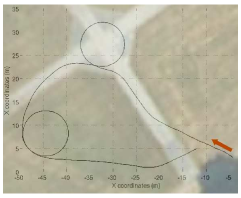
Figure 4. Experimental robot and embedded sensors

- An RTK-GPS. The mobile antenna is settled up to the middle of the rear axle, providing an absolute position within an accuracy of ±2cm. Thanks to this sensor, deviations with respect to the desired path as well as the velocity are known.
- A low cost IMU. This sensor provides three accelerations and three angular velocities, allowing to estimate lateral inclination and to feed the observer with the yaw rate.

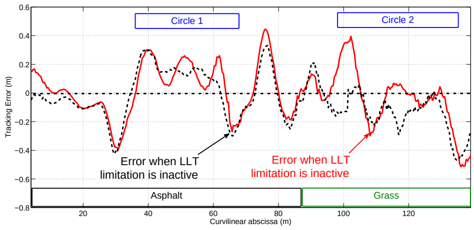
Other sensors depicted in figure 4 (cameras and laser) are not used in the application described in this paper.

5.2 Motion control and rollover prevention

In order to point out the efficiency of the velocity moderation in order to ensure the robot integrity in the framework of path tracking, the proposed algorithm is here demonstrated only regarding the rollover prevention. The path to be followed, depicted in figure 5(a) is composed of two successive circles: one to the right, performed on asphalt, and the other to the left, performed on wet grass.



(a) Reference path



(b) Tracking error with and without speed limitation

Figure 5. Comparison of tracking errors with/without integrity preservation

The performances of the proposed algorithms are here investigated with a target speed of $4m.s^{-1}$, and path tracking is run two times: first without the velocity moderation (velocity is constant and equal to 4m/s), and secondly with the limitation active, with a desired threshold of ± 0.35 for the Lateral Load Transfer. We can first notice that the path tracking accuracy is independent from the velocity (both tracking errors are superposed) and despite the speed variation, depicted in figure 6, the tracking error does not exceed 40cm (during a transient phase), and does not rely on the kind of terrain (asphalt or wet grass do not influence the tracking accuracy). Classical path tracking control (typically neglecting sideslip angles), does not permit to reach such a precision, and huge errors (around 2 m, but not depicted here) are recorded during curve following on the grass part.

From a rollover point of view, when achieving the trajectory without speed moderation, the LLT reaches ± 0.4 pending on the curve and grip conditions, as depicted in figure 6 (i.e. above the desired threshold of 0.35). The interest of using speed limitation for LLT control is then clearly highlighted, since the LLT does not exceed 0.35 when integrity preservation is active.

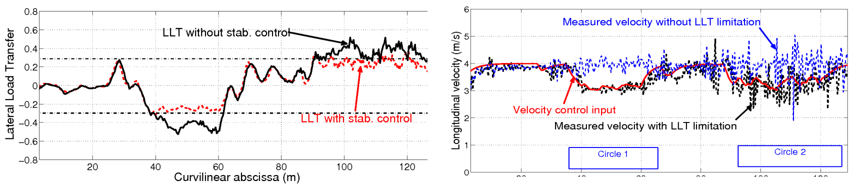


Figure 6. Speed limitation and corresponding LLT recorded (target velocity of $4m.s^{-1}$)

In order to keep the LLT within the desired range, the computed maximal speed is inferior to the desired speed of $4m.s^{-1}$ and is adapted with respect to estimated grip conditions. As it can be seen at the right in figure 6, the maximal computed speed converges to a constant value of $3m.s^{-1}$ during the first bend (on asphalt), while it varies between 2.8 up to $3.5m.s^{-1}$ during the second curve on grass, for maintaining the LLT on the desired value of 0.35. This shows the efficiency of the algorithm in preserving the robot stability and motion accuracy, whatever the ground conditions and path to be followed. Other experiments achieved at higher speed demonstrate the efficiency of the approach on both tracking accuracy and stability preservation.

6 Conclusion

This paper proposes a predictive and adaptive approach for path tracking, enabling an accurate motion control at high speed in off-road context, and ensuring the robot integrity. The efficiency of the proposed approach has been investigated through full-scale experiments. If the speed modulation permits to preserve the accuracy, the developments here proposed are part of a project[1], in which the addition of non-classical degrees of freedom (e.g active anti-roll bar) are investigated to increase the robot stability. It supposes a higher level of prediction based on Numeric Terrain Model computation.

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